

SUBMILLIMETER NARROW EMISSION LINES FROM
THE INNER ENVELOPE OF IRC+10216NIMESH A. PATEL¹, KEN H. YOUNG¹, SANDRA BRÜNKEN¹, ROBERT W. WILSON¹,
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ABSTRACT

A spectral-line survey of IRC+10216 in the 345 GHz band has been undertaken with the Submillimeter Array. Although not yet completed, it has already yielded a fairly large sample of narrow molecular emission lines with line-widths indicating expansion velocities of $\sim 4 \text{ km s}^{-1}$, less than 3 times the well-known value of the terminal expansion velocity (14.5 km s^{-1}) of the outer envelope. Five of these narrow lines have now been identified as rotational transitions in vibrationally excited states of previously detected molecules: the $v=1$, $J=17-16$ and $J=19-18$ lines of Si^{34}S and ^{29}SiS and the $v=2$, $J=7-6$ line of CS. Maps of these lines show that the emission is confined to a region within $\sim 60 \text{ AU}$ of the star, indicating that the narrow-line emission is probing the region of dust-formation where the stellar wind is still being accelerated.

Subject headings: stars: individual (IRC+10216) — stars: late-type — circumstellar matter — submillimeter — radio lines: stars

1. INTRODUCTION

Massive circumstellar envelopes of Asymptotic Giant Branch (AGB) stars are believed to be a major contributor of molecules and grains to the interstellar medium. IRC+10216 (CW Leo), at a distance of 150 pc, is the archetypal AGB carbon star with a high mass-loss rate ($> 10^{-5} \text{ M}_{\odot} \text{ yr}^{-1}$) (Young et al. 1993; Crosas & Menten 1997). Owing to its proximity, this star is an ideal target for detailed studies of physical and chemical processes in AGB circumstellar envelopes (e.g. Olofsson et al. 1982). Nearly 60 molecular species have been discovered in its circumstellar shell from single-dish spectral-line surveys (Kawaguchi et al. 1995; Avery et al. 1992; Groesbeck et al. 1994; Cernicharo et al. 2000; He et al. 2008).

Interferometric mapping allows us to check predictions of abundances of various molecular species as a function of radius in the circumstellar envelope. “Parent” molecules, such as CO, C_2H_2 , CS, HCN, & SiS, are formed in the stellar atmosphere in thermo-chemical equilibrium (Tsuji 1964, 1973). Once they get levitated to a distance from the star at which the density is too low for chemical reactions, their abundances “freeze out” at the values prevailing in that region (McCabe et al. 1979). At around that distance ($\sim 20 \text{ AU}$), the temperature has dropped below the dust condensation value ($\sim 1200 \text{ K}$) and dust grains start forming (Monnier et al. 2000). Radiation pressure accelerates the grains and, by friction, the molecules too, in an outflow which, for IRC+10216, reaches a terminal velocity of 14.5 km s^{-1} . In the outer parts of the expanding envelope, a rich carbon-dominated photo chemistry driven by the ambient ultraviolet field produces species such as CN and C_4H

whose mostly optically thin emission can be observed as ring-like distributions with radii, at a few times 10^{16} – 10^{17} cm depending on the chemical reactions at work (see the reviews of Glassgold 1996; Ziurys 2006).

At submillimeter wavelengths, we can observe lines requiring elevated excitation conditions, allowing us to probe the physical conditions in the inner circumstellar envelope (radius $\lesssim 10^{16} \text{ cm}$) where densities and temperatures are relatively high (temperatures ~ 100 – 1000 K , column densities $\sim 10^{22}$ – 10^{24} cm^{-2}) (Keady & Ridgway 1993).

We have begun a spectral-line survey of IRC+10216 with the Submillimeter Array⁵ (SMA, Ho et al. 2004). Previous 345 GHz single-dish line surveys include those done with the JCMT (Avery et al. 1992) and CSO (Groesbeck et al. 1994) in the frequency ranges of 339.6–364.6 GHz and 330.2–358.1 GHz, respectively. Our SMA line survey will eventually cover the frequency range of 300–355 GHz with higher sensitivity and spatial resolution than previous surveys; about 40% of the survey has so far been completed. The frequency range 300–330 GHz will be observed for the first time. Here we present several new results, including the discovery of many lines having narrow widths, and detections of vibrationally excited rotational transitions in SiS, ^{29}SiS , Si^{34}S and CS. A full account of the observed lines will be presented on completion of the survey.

2. OBSERVATIONS AND DATA REDUCTION

We observed IRC+10216 with the SMA in 2007 February in the subcompact configuration with baselines from 9.5 m to 69.1 m in the frequency range of 300 to 355 GHz. To follow up on some of the detected narrow lines with higher angular and spectral resolution, we repeated the observations at 337.5 GHz with the SMA in the extended configuration on 2008 February 19. The base-

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line lengths in this configuration range from 44.2 m to 225.9 m. The synthesized beam sizes were $3'' \times 2''$ and $0.8'' \times 0.6''$ in the subcompact and extended array observations, respectively. Table 1 summarizes the observational parameters on the five tracks of observations which are relevant for the data presented here. The duration of each track was from 7 to 9 hours. The phase center was $\alpha(2000) = 09^h47^m57.38^s$, $\delta(2000) = +13^\circ16'43.70''$ for all observations. All the tracks in subcompact configuration were carried out in mosaiced mode, with 5 pointings with offsets in RA and DEC: $(0'', 0'')$ and $(\pm 12'', \pm 12'')$. The extended configuration observations were carried out with single pointing toward IRC+10216. Titan and the quasars 0851+202 and 1055+018 were observed every 20 minutes for gain calibration. The spectral band-pass was calibrated using observations of Mars and Jupiter. Absolute flux calibration was determined from observations of Titan and Ganymede.

The visibility data were calibrated using the *Miriad* package (Sault, Teuben & Wright 1995). The mosaiced images are deconvolved using the *Miriad* task *mosdef*; the resulting synthesized beams are summarized in Table 1. Maps of continuum emission show the peak to have a position offset of $(\Delta\alpha, \Delta\delta) \approx (0.07'', 0.2'')$ from the phase center position quoted above. The absolute position measurements in the continuum emission are estimated to be accurate to $\sim 0.1''$. Taking into account the proper motion of IRC+10216 of $(\dot{\alpha}, \dot{\delta}) \approx (26, 4)$ mas yr^{-1} determined by Menten et al. (2006) our position is, within the mutual uncertainties consistent with that determined by those authors. The continuum emission was unresolved at the highest angular resolution of $\sim 0.8''$. The integrated continuum flux density was 0.84 Jy at 301.1 GHz and 1.17 Jy at 337.5 GHz, with an uncertainty of about 15% in the absolute flux calibration. All the spectra shown below were produced by integrating the continuum-subtracted line intensity in a $2'' \times 2''$ rectangle centered on continuum peak (by means of the *Miriad* task *imspec*).

3. EXPANSION VELOCITIES

Within a $3''$ beam a total of 92 lines were detected in the first phase of the SMA line survey of IRC+10216 at the central position. Truncated parabolic line profiles were fitted using the CLASS package (using the *shell* model for the line-profile) with one of the fitted parameters being V_{exp} , the expansion velocity of the circumstellar shell. From this sample, 25 lines have $V_{exp} \leq 7 \text{ km s}^{-1}$ and of these, 12 are as yet unidentified. Several are tentatively identified to be lines of salts such as KCN, NaCl and NaCN. Some of the lines may result from known molecules in vibrationally excited states, such as the $v_3=1$ $15_{7,9} - 14_{7,8}$, $15_{7,8} - 14_{7,7}$ doublet of SiCC at 345727.3 MHz. Figure 2 shows a sample spectrum toward IRC+10216 observed on 2008 February 9 over a 2 GHz wide band centered at 337.5 GHz. A comparison with the line survey of Groesbeck et al. (1994) (see their Figure 1) shows that only the C^{34}S $J=7-6$ line at 337.396 GHz was detected in their observations. All of the new narrow lines were missed in this previous survey due to poorer sensitivity. Here we present results on the lines which are securely identified as rotational transitions in vibrationally excited states of molecules that are well known to be abundant in IRC+10216's envelope.

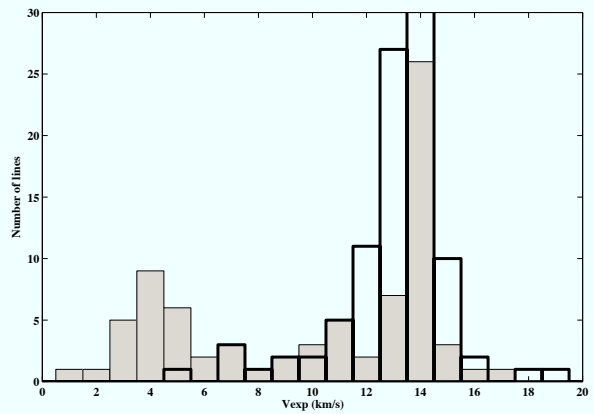


FIG. 1.— Distribution of expansion velocities derived from lines detected in the circumstellar envelope of IRC+10216. The uncertainty in V_{exp} is $\sim 0.2 \text{ km s}^{-1} (1\sigma)$. White bars with bold outlines are from the recent line survey of He et al. (2008) which is representative of all single-dish line surveys toward IRC+10216 at cm to submm wavelengths. The bin at 14 km s^{-1} is shown truncated here; it actually consists of 170 lines. Grey bars represent SMA observations, showing a new population of narrow lines which peaks at $\sim 4 \text{ km s}^{-1}$.

In previous single-dish line surveys of IRC+10216 (Cernicharo et al. 2000; Kawaguchi et al. 1995; Avery et al. 1992; Groesbeck et al. 1994) V_{exp} is not tabulated, but it can be seen from published spectra to be $\sim 14.5 \text{ km s}^{-1}$ for all lines. From the latest published line survey by He et al. (2008) (see their Table 9.), we can plot a distribution of V_{exp} which is shown in Figure 1 as empty bars with bold outlines. This histogram peaks at 14 km s^{-1} . The distribution of V_{exp} from our line survey is shown in Figure 1 as grey bars. Our line survey shows a peak in the same bin of 14 km s^{-1} but reveals a significant number of narrow lines with velocities around $\sim 4 \text{ km s}^{-1}$. Both histograms show a continuous distribution of expansion velocities between these two peaks at 4 and 14 km s^{-1} .

Lines with $V_{exp} \leq 10 \text{ km s}^{-1}$ from IRC+10216 have been reported by Highberger et al. (2000) and were assigned as vibrationally excited SiS and CS lines. He et al. (2008) found four lines with $V_{exp}=7-10.2 \text{ km s}^{-1}$ (see their Table 14) – all from vibrationally excited SiS. Narrow maser lines in IRC+10216 from SiS and HCN were reported by Fonfría-Expósito et al. (2006) and Schilke & Menten (2003), respectively. Savik-Ford et al. (2004) detected OH – which has a narrow width (5.8 km s^{-1}), but this line appears at -37 km s^{-1} , blue-shifted with respect to the systemic velocity of the star of -26 km s^{-1} . All the narrow lines we have observed are centered at the systemic velocity of about -26 km s^{-1} to within $\sim 2 \text{ km s}^{-1}$. Infrared molecular line profiles in the $10 \mu\text{m}$ band were observed and analyzed by Keady & Ridgway (1993). They proposed (see their Figure 3) an expansion velocity as a function of radius with: (1) $V_{exp} = 3 \sim 4 \text{ km s}^{-1}$ from $1 \sim 8 R_*$, (2) rapid acceleration from 4 to 11 km s^{-1} from 8 to $10 R_*$ and (3) slower acceleration from 11 km s^{-1} to the terminal velocity of 14 km s^{-1} from 10 to $20 R_*$. The histogram of expansion velocities (Figure 1) peaks at $\sim 4 \text{ km s}^{-1}$ and $\sim 14 \text{ km s}^{-1}$, consistent with this velocity structure.

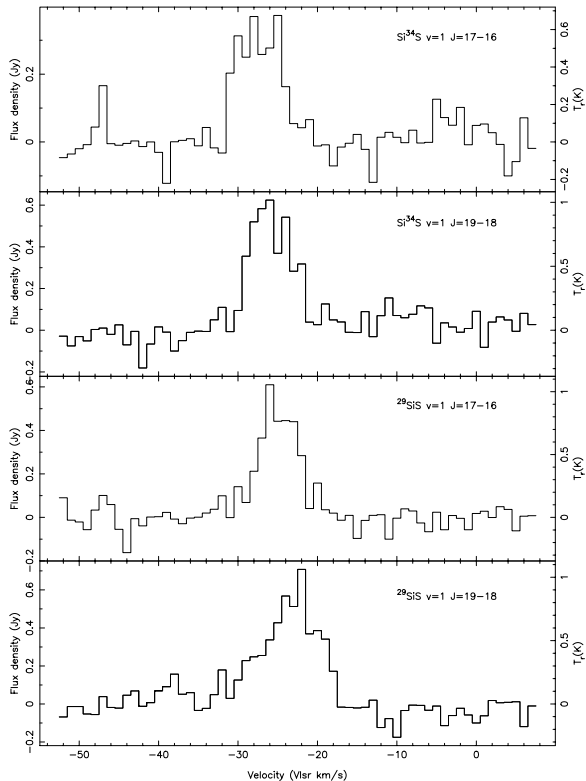


FIG. 4.— Spectra of vibrationally excited rotational lines in isotopes of SiS obtained from the imaged data cube. The flux density was calculated over the area enclosed in a $2''$ square centered on the star. See also Table 2.

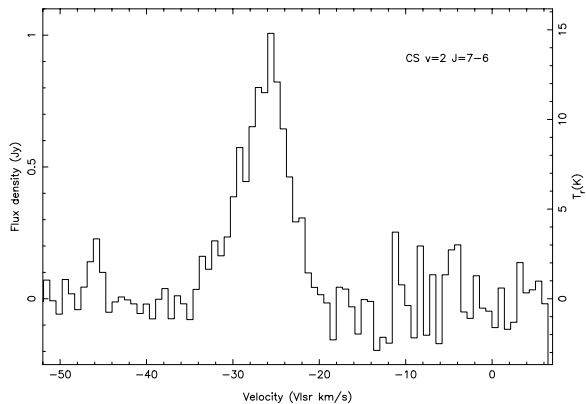


FIG. 5.— Spectrum of CS $v=2$ $J=7-6$ emission at 337912.19 GHz. See Figure 4 caption and also Table 2.

jarrabal et al. 1986). In subcompact configuration observations with angular resolution of $\sim 3''$, the emission appears highly concentrated and unresolved. There is no emission detected at the angular radius of $\sim 12''$ (where several other species have shown a peak in abundance in previous interferometric maps). The observations of this line were repeated in the extended configuration of the SMA at a beam size of $0.8''$, confirming that the emission is unresolved. The deconvolved source size is $< 0.2''$. The lower limit for brightness temperature is 237 K. Assuming an excitation temperature of 550 K, we estimate a column density of $7 \times 10^{17} \text{ cm}^{-2}$ and a lower limit for CS abundance with respect to H_2 of 9.3×10^{-6} within a radius of $\sim 4.5 \times 10^{14} \text{ cm}$ ($\sim 7R_*$).

Previous interferometric observations of the $v=1$, $J=5-4$ line show the emission to be within a radius of $0.35''$ ($\sim 10 R_*$ or $\sim 7 \times 10^{14} \text{ cm}$) (Lucas and Guelin 1999). Young et al. (2004) derived a lower limit on the CS abundance to be 3.4×10^{-9} within $\sim 34 R_*$. From single-dish observations of CS $v=1$, $J=3-2$, $6-5$ and $7-6$ lines, Highberger et al. (2000) estimate an abundance of $3-7 \times 10^{-5}$ relative to H_2 . From comparison with the CS radial abundance predicted by chemical models, we conclude, as did Young et al. (2004), that the model of Millar et al. (2001) predicts too low a value ($\sim 10^{-11}$) at the radius of $\sim 10^{16} \text{ cm}$. In this model, assuming CS to be a parent molecule (see Figure 1, right-panel, in Millar et al. 2001), the initial abundance is still lower by about an order of magnitude relative to that derived from submillimeter observations. Moreover, the drop in CS abundance with radius (owing to the production of other sulphur-bearing molecules), is too small, and not consistent with the compact distribution of CS seen in the SMA observations. There is better agreement in a more recent study of non-equilibrium chemistry of the inner wind, which takes into account shocks induced by stellar pulsation (Cherchneff 2006), although these models seem more relevant for S stars ($\text{C/O} \approx 1$).

The CS $v=2$, $J=7-6$ transition requires extreme excitation conditions since it corresponds to an energy $E_u/k=3707 \text{ K}$. As noted by Highberger et al. (2001), even for the $v=1$ line, collisional excitation with H_2 would require very high gas densities ($\sim 1-5 \times 10^{14} \text{ cm}^{-3}$). This line emission is most plausibly excited by $8 \mu\text{m}$ stellar thermal radiation.

6. CONCLUSIONS

Preliminary results from the SMA line survey of IRC+10216 have yielded a population of narrow lines with expansion velocities of $\sim 4 \text{ km s}^{-1}$. About half of these can be assigned to vibrationally excited rotational transitions of abundant species such as CS, SiS and their isotopomers. The emission is found to occur in a very compact region smaller than $0.2''$ around the star. This is thought to be the region where dust is forming in the envelope and in which the material has just begun accelerating and has yet to attain the terminal velocity of $\sim 14 \text{ km s}^{-1}$. The CS $v=2$, $J=7-6$ line is most likely radiatively excited, because collisional excitation would require an unrealistically high gas density and abundance of CS.

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TABLE 1
SUMMARY OF OBSERVATIONS

Date	SMA configuration	Tuning	Synthesized beam	$\tau_{225\text{GHz}}$	T_{sys} (SSB, K)
2007 February 7	subcompact	299.1 GHz (LSB)	$3.''2 \times 2.''4$, P.A.= -4°	0.08	180–270
2007 February 8	subcompact	301.1 GHz (LSB)	$3.''3 \times 2.''4$, P.A.= -6°	0.09	160–230
2007 February 9	subcompact	337.5 GHz (LSB)	$3.''0 \times 2.''4$, P.A.= -8°	0.08	180–350
2007 February 12	subcompact	334.4 GHz (LSB)	$3.''0 \times 2.''2$, P.A.= -3°	0.05	130–260
2008 February 19	extended	337.5 GHz (LSB)	$0.''8 \times 0.''6$, P.A.= -88°	0.03	100–250

TABLE 2
SUMMARY OF NARROW LINES

Species	Transition	Rest frequency ¹ (MHz)	Catalog freq ² . (MHz)	V_{exp} (km s ⁻¹)	Peak flux density ³ (Jy)	Integrated flux density (Jy km s ⁻¹)	Deconvolved size	T_B ⁴ (K)
CS	v=2 J=7–6	337913.246 \pm 0.18	337912.189	5.1 \pm 0.1	0.78	7.0	< 0.''2	>237.0
Si ³⁴ S	v=1 J=17–16	298630.441 \pm 0.69	298629.989	4.5 \pm 0.4	0.36	2.6	< 1.''9 \times 0.''2	>138.7
Si ³⁴ S	v=1 J=19–18	333733.581 \pm 0.32	333731.998	5.7 \pm 0.1	0.49	4.5	< 2.''3 \times 0.''5	>183.3
²⁹ SiS	v=1 J=17–16	301390.406 \pm 0.25	301388.939	4.8 \pm 0.2	0.52	3.8	< 1.''9 \times 0.''8	>198.3
²⁹ SiS	v=1 J=19–18	336819.842 \pm 0.32	336814.954	7.5 \pm 0.1	0.50	4.6	< 0.''9 \times 0.''6	>152.9

¹ Assuming a systemic velocity of -26.2 km s⁻¹. ² From the Cologne Database of Molecular Spectroscopy. ³ Typical uncertainty is 0.1 Jy. ⁴ Lower limit in brightness temperature assuming source size of $0.''2 \times 0.''2$

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